ORDECSYS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

A stochastic dynamic game of the 2050 European Energy Roadmap with CCS

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Introduction

- European Commission has defined a roadmap with an objective of 80% GHG reduction in 2050 compared to 1990 levels
- Carbon Capture and Sequestration technologies are considered as potential backstop technologies (up to 14% of total abatements according to IEA)
- CCS deployment is highly uncertain with technical, social and legislative issues

Questions:

1. How to share the burden of the GHG target? How to design a fair agreement among EU countries?
2. What impacts of CCS uncertainty on such agreements?

A noncooperative dynamic game

Assumptions:

1. **A safety emissions budget** *Bud* is distributed among the players. Let $\theta_j \in (0,1)$ be the share of player j, with $\sum_{j=1}^{m} \theta_j = 1$.
2. **A competitive market for emissions permits**, which clears at each period. Let ω_j^t be the vector of permits for country j at period t.
3. **CCS penetration**. We denote ccs_j^t the amount of emissions of country j sequestered at period t at cost C^t and $\overline{ccs}_j^t$ the upper bound for sequestration for country j at period t.

Model: Then we consider the game where each player j controls the permit allocations schedule $(\omega_j^t : t = 0, \ldots, T-1)$ with $\Omega^t = \sum_{j=1}^{m} \omega_j^t$ and tries to achieve

$$\max_{\omega_j, ccs_j \leq \overline{ccs}_j} \left\{ \sum_{t=0}^{T-1} \beta_j^t (\pi_j^t(\mathbf{e}_j^t(\Omega^t)) + p^t(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + \mathrm{ccs}_j^t) - C^t \mathrm{ccs}_j^t \right\},$$

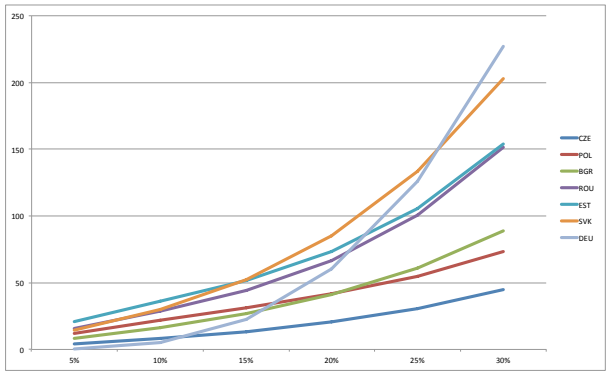
subject to actions chosen by the other players and under the budget sharing constraint

$$\sum_{t=0}^{T-1} \omega_j^t \leq \theta_j \mathrm{Bud}. \tag{1}$$

Here $\pi_j^t(e_j^t)$ represents the economic benefits obtained from emissions by country j, at time t.

Numerical implementation

- four decades 2020, 2030, 2040, 2050
- Bud=99 Gt CO_2
- $\pi_j^t(e_j^t)$ are estimated from 200 runs of the CGE GEMINI-E3



- $\overline{ccs}_j^t$ are based on CO_2 storage capacity and emissions from electricity generation, the CCS penetration rate is assumed to be linear between 2030 and 2050
- The cost of CCS is 110 \$/tCO_2 and half of emissions from electricity generation can be sequestered in 2050
- $\beta_j = 5\%$
- θ_j are based on the following rules:
  - Sovereignty - Allocations are proportional to emissions in 2010
  - Ability to pay - Abatements are proportional to GDP in 2010
  - Egalitarian - Allocations are proportional to population in 2010

Nash equilibrium: deterministic case

Cumulative discounted welfare losses (in % of cumulative discounted household consumption)

	Sovereignty	Ability	Egalitarian
Austria			
Belgium			
Bulgaria			
Cyprus			
Czech Republic			
Germany			
Denmark			
Estonia			
Finland			
France			
Great Britain			
Greece			
Croatia			
Hungary			
Ireland			
Italy			
Latvia			
Lithuania			
Luxembourg			
Malta			
Netherlands			
Poland			
Portugal			
Romania			
Spain			
Slovak Republic			
Slovenia			
Sweden			
EU-28	0.59	0.59	0.59

Nash equilibrium: deterministic case

Cumulative discounted welfare losses (in % of cumulative discounted household consumption)

	Sovereignty	Ability	Egalitarian
Austria	0.36		
Belgium	0.82		
Bulgaria	-7.74		
Cyprus	9.67		
Czech Republic	-11.29		
Germany	-1.60		
Denmark	1.66		
Estonia	-2.16		
Finland	0.34		
France	1.68		
Great Britain	1.16		
Greece	7.08		
Croatia	5.90		
Hungary	0.42		
Ireland	2.27		
Italy	1.24		
Latvia	3.78		
Lithuania	-1.61		
Luxembourg	5.14		
Malta	4.66		
Netherlands	-1.10		
Poland	-3.59		
Portugal	1.12		
Romania	0.02		
Spain	1.76		
Slovak Republic	-0.84		
Slovenia	1.85		
Sweden	2.27		
EU-28	0.59	0.59	0.59

Nash equilibrium: deterministic case

Cumulative discounted welfare losses (in % of cumulative discounted household consumption)

	Sovereignty	Ability	Egalitarian
Austria	0.36	2.57	
Belgium	0.82	1.56	
Bulgaria	-7.74	-18.17	
Cyprus	9.67	-4.91	
Czech Republic	-11.29	-16.54	
Germany	-1.60	1.12	
Denmark	1.66	-1.18	
Estonia	-2.16	-11.66	
Finland	0.34	0.81	
France	1.68	2.72	
Great Britain	1.16	1.03	
Greece	7.08	-8.19	
Croatia	5.90	0.54	
Hungary	0.42	-0.72	
Ireland	2.27	0.19	
Italy	1.24	2.28	
Latvia	3.78	-1.06	
Lithuania	-1.61	-1.62	
Luxembourg	5.14	-1.28	
Malta	4.66	-1.07	
Netherlands	-1.10	0.88	
Poland	-3.59	-11.13	
Portugal	1.12	0.35	
Romania	0.02	-3.92	
Spain	1.76	0.18	
Slovak Republic	-0.84	-2.98	
Slovenia	1.85	0.12	
Sweden	2.27	5.00	
EU-28	0.59	0.59	0.59

Nash equilibrium: deterministic case

Cumulative discounted welfare losses (in % of cumulative discounted household consumption)

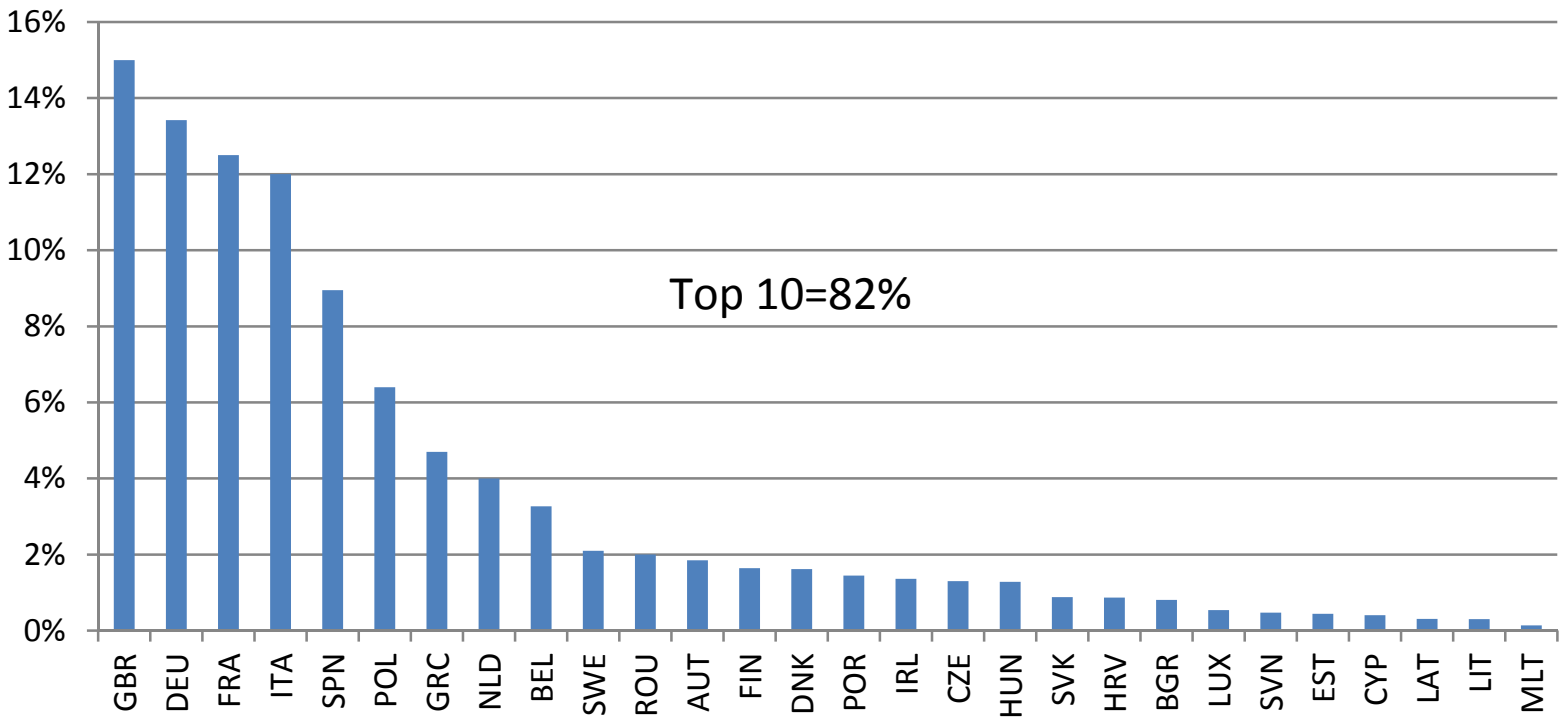
	Sovereignty	Ability	Egalitarian
Austria	0.36	2.57	0.92
Belgium	0.82	1.56	2.83
Bulgaria	-7.74	-18.17	-14.09
Cyprus	9.67	-4.91	9.67
Czech Republic	-11.29	-16.54	-4.70
Germany	-1.60	1.12	-0.18
Denmark	1.66	-1.18	2.35
Estonia	-2.16	-11.66	6.92
Finland	0.34	0.81	2.81
France	1.68	2.72	0.52
Great Britain	1.16	1.03	1.39
Greece	7.08	-8.19	7.08
Croatia	5.90	0.54	0.17
Hungary	0.42	-0.72	-3.69
Ireland	2.27	0.19	2.76
Italy	1.24	2.28	0.65
Latvia	3.78	-1.06	-2.32
Lithuania	-1.61	-1.62	-5.75
Luxembourg	5.14	-1.28	9.03
Malta	4.66	-1.07	4.66
Netherlands	-1.10	0.88	1.65
Poland	-3.59	-11.13	-1.80
Portugal	1.12	0.35	-1.87
Romania	0.02	-3.92	-10.47
Spain	1.76	0.18	0.47
Slovak Republic	-0.84	-2.98	-1.93
Slovenia	1.85	0.12	1.85
Sweden	2.27	5.00	1.08
EU-28	0.59	0.59	0.59

Nash equilibrium: deterministic case

Cumulative discounted welfare losses (in % of cumulative discounted household consumption)

	Sovereignty	Ability	Egalitarian	Fair
Austria	0.36	2.57	0.92	0.50
Belgium	0.82	1.56	2.83	0.48
Bulgaria	-7.74	-18.17	-14.09	0.60
Cyprus	9.67	-4.91	9.67	0.54
Czech Republic	-11.29	-16.54	-4.70	0.55
Germany	-1.60	1.12	-0.18	0.63
Denmark	1.66	-1.18	2.35	0.56
Estonia	-2.16	-11.66	6.92	0.55
Finland	0.34	0.81	2.81	0.59
France	1.68	2.72	0.52	0.63
Great Britain	1.16	1.03	1.39	0.61
Greece	7.08	-8.19	7.08	0.52
Croatia	5.90	0.54	0.17	0.59
Hungary	0.42	-0.72	-3.69	0.53
Ireland	2.27	0.19	2.76	0.53
Italy	1.24	2.28	0.65	0.61
Latvia	3.78	-1.06	-2.32	0.52
Lithuania	-1.61	-1.62	-5.75	0.47
Luxembourg	5.14	-1.28	9.03	0.49
Malta	4.66	-1.07	4.66	0.55
Netherlands	-1.10	0.88	1.65	0.58
Poland	-3.59	-11.13	-1.80	0.58
Portugal	1.12	0.35	-1.87	0.56
Romania	0.02	-3.92	-10.47	0.50
Spain	1.76	0.18	0.47	0.57
Slovak Republic	-0.84	-2.98	-1.93	0.47
Slovenia	1.85	0.12	1.85	0.41
Sweden	2.27	5.00	1.08	0.60
EU-28	0.59	0.59	0.59	0.59

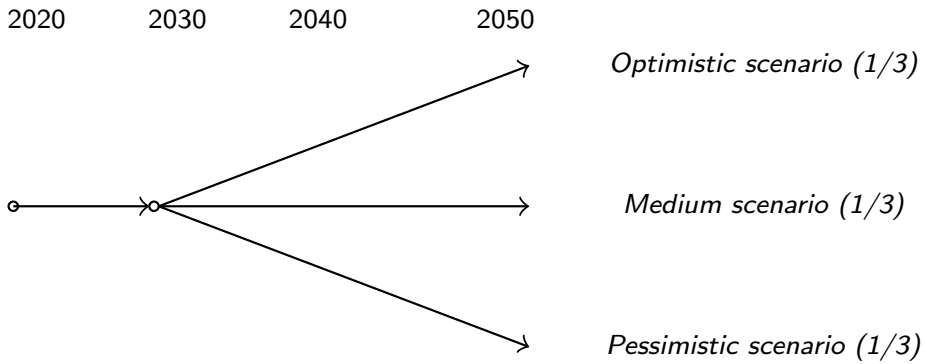
EU burden sharing in % *Fair solution*



Stochastic analysis on CCS deployment

We define three contrasted scenarios of CCS deployment

- **Optimistic**: The cost of CCS is 55 $/tCO$_2$ and CCS technologies are expected to sequester all emissions from gas and coal power plants in 2050.
- **Pessimistic**: The cost of CCS is 165 $/tCO$_2$ and CCS technologies are expected to sequester quarter of emissions from gas and coal power plants in 2050.
- **Medium**: Figures = deterministic case



European emissions profile

Deterministic case

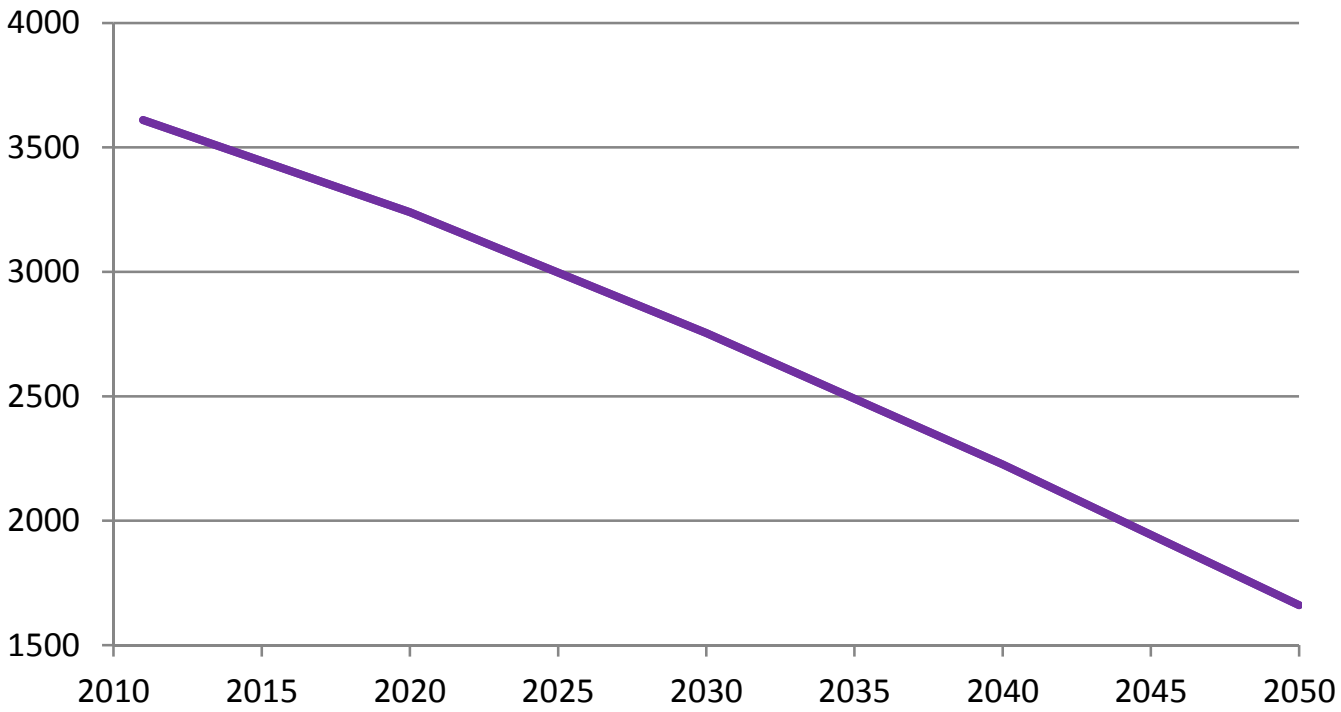


Figure: Emissions profile (in $MtCO_2$)

European emissions profile

Deterministic case *versus* without CCS

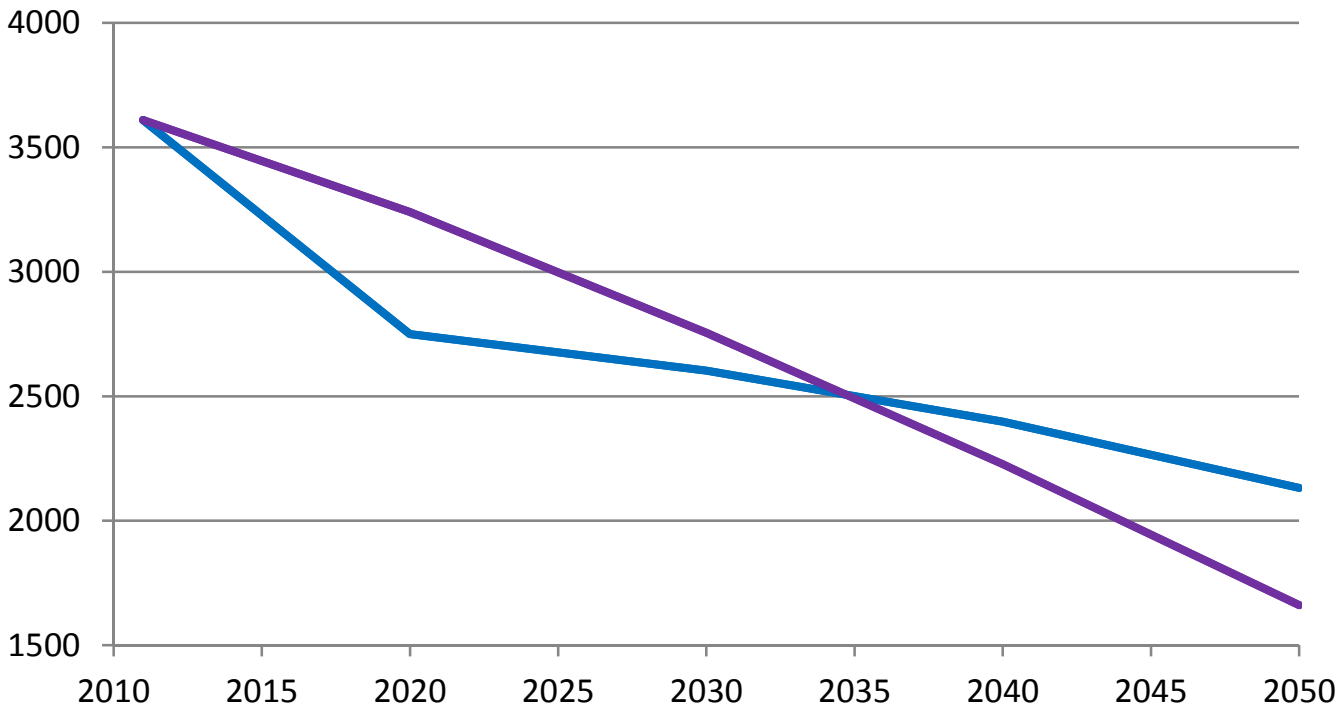


Figure: Emissions profile (in $MtCO_2$)

European emissions profile

Deterministic case *versus* stochastic case

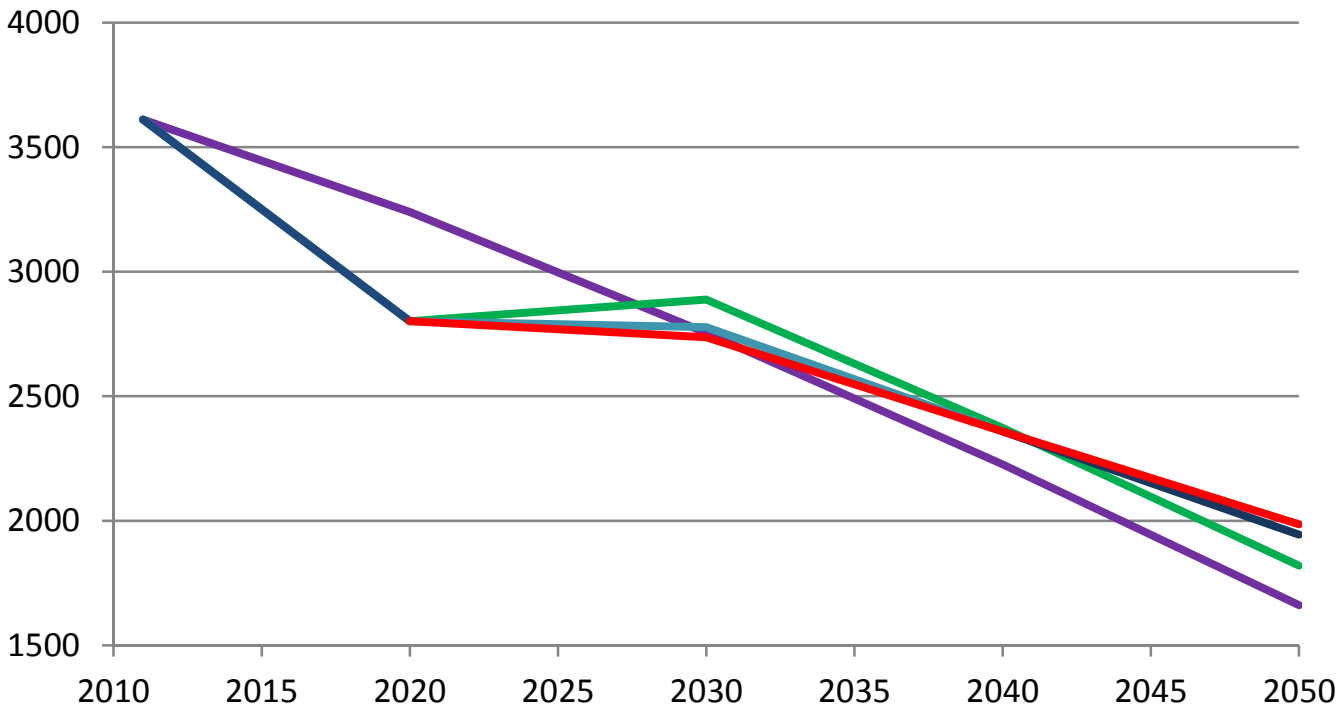


Figure: Emissions profile (in $MtCO_2$)

EU Welfare cost and CO_2 sequestered

	CO_2 price $ in 2050	Cumulative welfare loss in %	CO_2 sequestered in Gt CO_2	% of abatement
Deterministic case				
Without CCS	1103	1.2	–	–
With CCS	847	0.6	11.0	15%
Stochastic case				
Pessimistic	991	0.9	5.5	7%
Medium	761	0.6	11.1	15%
Optimistic	440	0.1	21.4	29%

Conclusion

- It is possible to design an agreement that equalizes the welfare cost between the 28 EU member states
- The implementation of an EU tradable permits market is crucial as it allows to equalize marginal abatement costs
- The negotiations of the next burden sharing will become more complex and more challenging within 28 diverse Member States
- CCS deployment has a significant impact and its uncertainty has to be considered
- Postponement strategy for CO_2 abatement that we find within the deterministic scenario is no longer optimal in the stochastic case